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Infrared Radiation Transmittance and Pilot Vision Through Civilian Aircraft Windscreens

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16. Abstract

INTRODUCTION: In support of a Department of Homeland Security project, the Federal Aviation Administration´s Civil Aerospace Medical Institute measured the optical transmittance properties of aircraft windscreens. This paper focuses on windscreen transmittance in the infrared (IR) spectral region (780 – 4000 nm) of the electromagnetic spectrum. **METHOD:** Transmission measurements were performed on eight aircraft windscreens. Three windscreens were from large commercial jets (MD 88, Airbus A320, and Boeing 727/737); two from commercial, propeller-driven passenger planes (Fokker 27 and the ATR 42); one from a small private jet (Raytheon Aircraft Corporation Hawker Horizon); and two from small general aviation (GA), single-engine, propeller-driven planes (Beech Bonanza and Cessna 182). The two GA aircraft windscreens were plastic (polycarbonate); the others were multilayer (laminated) composite glass. **RESULTS:** The average transmittance for both glass laminate and plastic windscreens in the IR-A region (780 – 1400 nm) varied considerably (47.5% ± 11.7%), with glass windscreens consistently attenuating more IR than plastic windscreens. The average difference in transmittance between the two materials fluctuated (27.3% ± 15.9%) throughout the first half of the IR-B spectrum (1400 – 3000 nm) up to approximately 2200 nm when transmittance dropped below 7%. The average transmittance for glass and plastic windscreens became negligible beyond 2800 nm. **CONCLUSION:** Aircraft windscreens provide a level of protection from potential ocular and skin hazards due to prolonged or intense exposure to IR radiation. The amount of protection is dependent on the type of windscreen material, the wavelength of the radiation, and angle of incidence. On average, laminated glass windscreens attenuate more IR than plastic. Additional research is recommended to confirm that the measured transmittance values for this sample of windscreens are typical of all aircraft windscreens currently in service and to evaluate the potential threat posed by new applications, such as IR lasers, in navigable airspace.

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CONTENTS

Infrared Radiation Transmittance and Pilot Vision Through Civilian Aircraft Windscreens

INTRODUCTION

An aircraft's windshield (i.e., windscreen) is vital for enhancing and protecting the pilot's vision. The transmittance of a windscreen material can affect visual performance while providing protection from harmful electromagnetic radiation. Transmittance may be determined by calculating the ratio of the total *radiant* or *luminous flux* that is transmitted to that which is incident on the surface of the windscreen. A high ratio indicates that incident radiation is transmitted efficiently through the windscreen, while a low ratio denotes lesser transmission.

Optical radiation is defined as the part of the electromagnetic spectrum that includes ultraviolet (UV), visible, and infrared (IR) radiation. The Commission Internationalè de l'Eclairage (CIE) Committee on Photobiology has provided spectral band designations that are convenient for discussing biological effects. These divisions in the optical spectrum are illustrated in Figure 1. Optical radiation can also be divided into two general regions with respect to their potential for eye damage: the retinal hazard region and the non-retinal hazard region. The wavelengths of the retinal hazard region include visible light (380 – 780 nm) and near IR (780 – 1400 nm) or IR-A radiation. The retinal hazard region identifies those bandwidths that are transmitted through the optical media of the eye (cornea, aqueous humor, crystalline lens, and vitreous humor) and focused onto the retina. The non-retinal hazard region refers to wavelengths that are mostly absorbed by anterior ocular tissues, without significant transmission to the retina. These bandwidths include UV radiation from 100 nm to 380 nm (UV-C, UV-B, and UV-A) and the IR bands with wavelengths greater than 1400 nm (IR-B and IR-C).

Excessive exposure to optical radiation is a concern to industrial hygienists, safety engineers, and public health officials for their potential as a hazard to health and safety. Aside from natural sources of radiation, such as the sun and cosmic background radiation, many man-made sources of optical radiation exist and are becoming increasingly accessible to the general public. Excessive exposure to these sources can also lead to adverse physiological consequences. Examples of these sources include lasers, mercury-vapor and xenon halogen lamps, welding devices, and infrared and germicidal lamps. These sources are frequently found in office settings, water treatment plants, hospitals, research laboratories, photo-etching production lines, graphic arts facilities, machine shops, tanning salons, and even in homes.

Much has been written about the dangers associated with exposure to excessive levels of visible and UV radiation in the National Airspace System (NAS) (1,2,3). Little has been reported concerning the potential hazards from

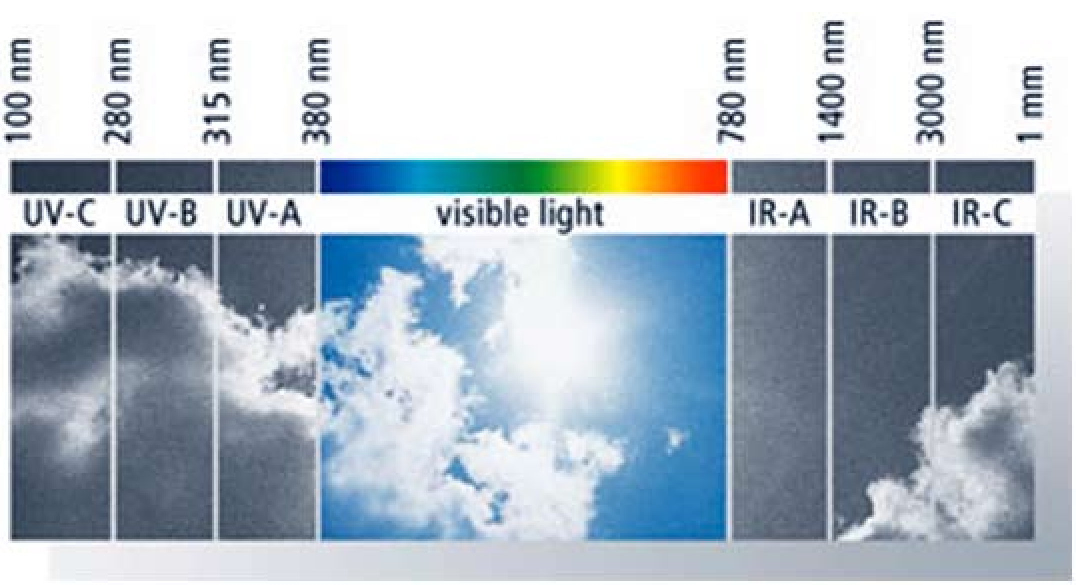

Figure 1. Optical radiation spectral bandwidths (CIE, 1970).

exposure to high levels of IR radiation. This is likely due to the perception that there is minimal risk of injury to aviators and the flying public from artificial and natural sources of IR radiation in the NAS. This is generally true for natural sources of IR radiation, including the sun. Most of the sun's ultraviolet radiation below 300 nm is absorbed by atmospheric ozone (O_3) and oxygen (O_2), while most of the visible and IR radiation striking the earth's atmosphere reaches the surface. The earth's surface absorbs visible light and re-emits much of the energy as IR radiation back into the atmosphere (4). Certain gases in the atmosphere, chiefly water vapor (H_2O) and carbon dioxide (CO_2), absorb IR and re-radiate it in all directions (5). Without the atmosphere to capture thermal energy from visible and IR radiation, the estimated average temperature of the earth would be a frigid 0° F, rather than a comfortable 59° F (6).

Under normal circumstances, naturally occurring atmospheric IR radiation is generally safe for ocular tissues and skin. Prolonged and/or repeated exposure to intense sources of IR, however, can result in retinal, corneal, and skin burns, as well as IR-induced cataracts. For normal outdoor activities, appropriate sunglasses and sunscreen is all that is necessary; however, with extreme exposure, special precautions are required. For example, astronomers are advised to never view a solar eclipse without a filter that attenuates all UV radiation, 99.997% of visible light, and 99.5% of IR-A (7). Glassblowers and anyone routinely working with molten materials should take similar precautions to protect their eyes from excessive exposure to IR radiation (8,9). It is commonly accepted that commercial pilots who fly at high altitudes for prolonged periods of time should invest in sunglasses that protect their eyes from exposure to both UV and excessive amounts of intense visible light (10,11). Ongoing scientific research and emerging technologies that employ IR lasers for use in the NAS have raised concerns about the possibility of aviation personnel and the public being accidentally exposed to harmful levels of IR radiation.

The Department of Homeland Security (DHS) Counter-Man Portable Air Defense System (MANPADS) Special Project Office requested that the Civil Aerospace Medical Institute's (CAMI) Vision Research Team evaluate the potential hazards to aviation personnel and the general public posed by the IR radiation emitted from these Counter-MANPADS systems. The measurement of aircraft windscreen transmittance was part of this laser safety assessment. Scientists from the United States Army Center for Health Promotion and Preventive Medicine (CHPPM), Aberdeen Proving Ground, MD, were enlisted to provide technical support. Based on the data provided by the CHPPM (12), an FAA report was published describing windscreen transmittance for UV radiation and visible light (13). The current report documents transmittance properties of a set of aircraft windscreens through the IR region (780 – 4000 nm) of the electromagnetic spectrum.

METHOD

Several aircraft windscreens were shipped from various aircraft maintenance facilities to CAMI's Vision Research Laboratory. Eight windscreens were selected from those available for testing. Three were from large commercial jets (MD 88, Airbus A320, and Boeing 727/737), one was from a smaller private jet (Raytheon Aircraft Corporation Hawker Horizon), two were from commercial, propeller-driven passenger planes (Fokker 27 and the ATR 42), and two were from smaller, single-engine propeller general aviation planes (Beech Bonanza and the Cessna 182). The Beech and Cessna windscreens were full windshields and made of a single-layer polycarbonate material, rather than the laminated glass that comprised the other six.

Instrumentation for testing included:

1) EG&G model 580 spectro-radiometer systems (with UV, visible, and IR gratings and housings); sorting filters; models 580-22A, 580-23A, and 580-25A photodiode detectors; and Palentronic AR582F indicator unit.
2) International Light Model 1700 radiometer with SED 623 broadband detector.
3) Ophir LaserStar radiometer system, with model 3A-P-SH thermopile detector.
4) Narrow pass filters: 1450 nm, 1540 nm, 1940 nm, 2050 nm, 2100 nm, 2200 nm, 2300 nm, and 2380 nm.
5) Long pass filters: 1600 nm and 2500 nm.
6) Sapphire window: transmission from UV to 4000 nm.
7) Light sources: deuterium lamp, 100-watt incandescent light, 250-watt heat lamp.
8) Light box and aircraft windscreen cart.
9) Miscellaneous laboratory mounts, filters, filter holders, and equipment.
10) Perkin Elmer UV/VIS/NIR model Lambda 900 spectrometer system.
11) Cold mirror and extended-range hot mirror.

Transmission measurements on the various windscreens were performed in a semi-darkened room. Two large tables were used: one for the light sources and the other to place the various optical detectors. A custom-made windscreen cart (Figure 2) was used to slide the windscreens in and out of the beam path between the two tables separating the light sources and detectors.

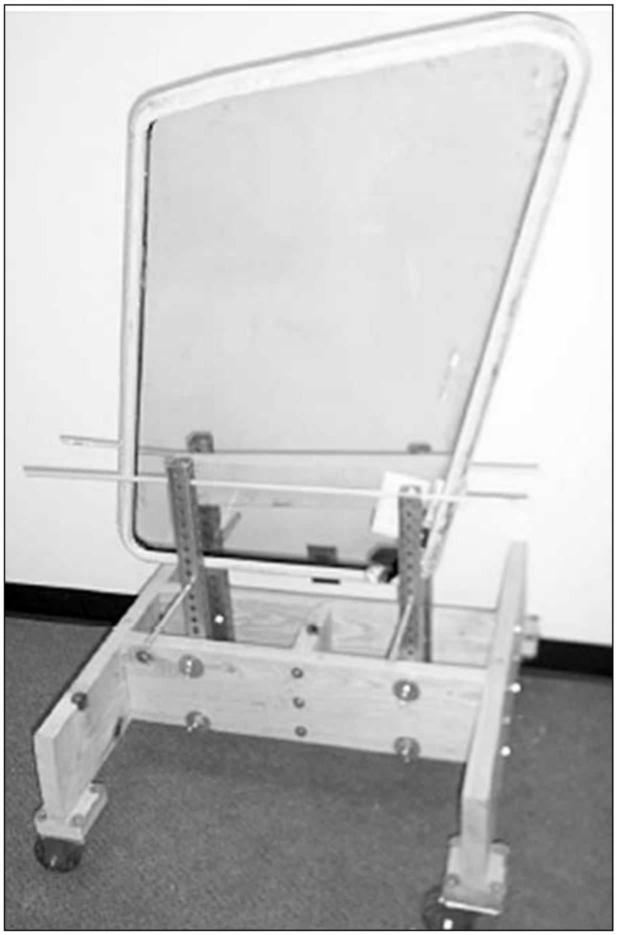

Figure 2. Custom-made windscreen cart for manipulating aircraft windscreens.

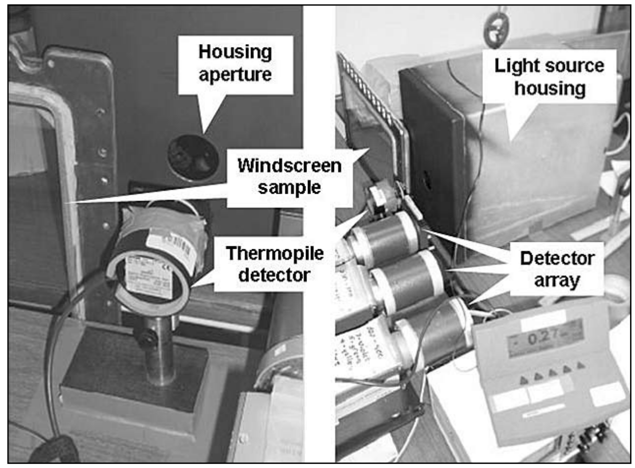

Figure 3. Detector and light source configuration.

Three monochromator systems were placed side-by-side and aligned with the appropriate light source, which was placed in a metal enclosure (Figure 3). For each windscreen and each spectral region, a baseline measurement was made with the windscreen moved to one side and then repeated with the windscreen placed between the light source and the detector. To confirm the data collected by the EG&G spectro-radiometers, the two polycarbonate (plastic) windscreens were cut and tested in a Lambda 900 spectrometer, resulting in good agreement. An attempt was made to cut a sample from the composite glass windscreens, but crazing of the sample made transmission measurements impossible.

For visible and near-infrared transmission (400 – 1250 nm) measurements, an ordinary incandescent 100-watt light bulb was sufficient for an illumination source due to the high transmission of the windscreens for visible and near-IR radiation. For wavelengths farther in the infrared, a 250-watt heat lamp was used for an illumination source. The EG&G Model 580-22A detector was used for measurements in the spectral region (400 – 800 nm), and the Model 580-23A detector was used in the spectral region (800 – 1400 nm). For wavelengths longer than 1400 nm, a sapphire window and a series of narrow pass filters were employed with a thermopile detector. Narrow pass filters were not available from 1550 nm to 1950 nm. Due to heating of components in the optical line of sight between the source and detector, not all background radiation could be eliminated. Therefore, the reported results for very low values of transmission, especially those for wavelengths greater than 2100 nm, reflect a maximum transmission, rather than an actual transmission measurement.

Due to the weight of the windscreens and the need to reposition the detectors and light source for various spectral regions, a single baseline was not practical. Therefore, a new baseline was usually created for each set of measurement conditions for each windscreen. Measuring two of the polycarbonate windscreens under both field and laboratory conditions served to validate the measurement method used on-site for all windscreens measurements and also to identify potential problem areas.

RESULTS

The transmittance values for individual glass laminate windscreens are summarized in Figure 4 and those for the two plastic windscreens in Figure 5.

The average transmittance data for both glass laminate and plastic windscreens are plotted in Figure 6. In the IR-A spectral region (780 – 1400 nm), average transmittance of the two materials varied (average difference = 47.5% ± 11.7%), with glass windscreens consistently attenuating more IR radiation than their plastic counterparts. Similarly, the average difference in transmittance fluctuated (27.3% ± 15.9%) throughout the first half of the IR-B spectrum (1400 – 3000 nm) up to approximately 2200 nm, where the transmittance for both materials

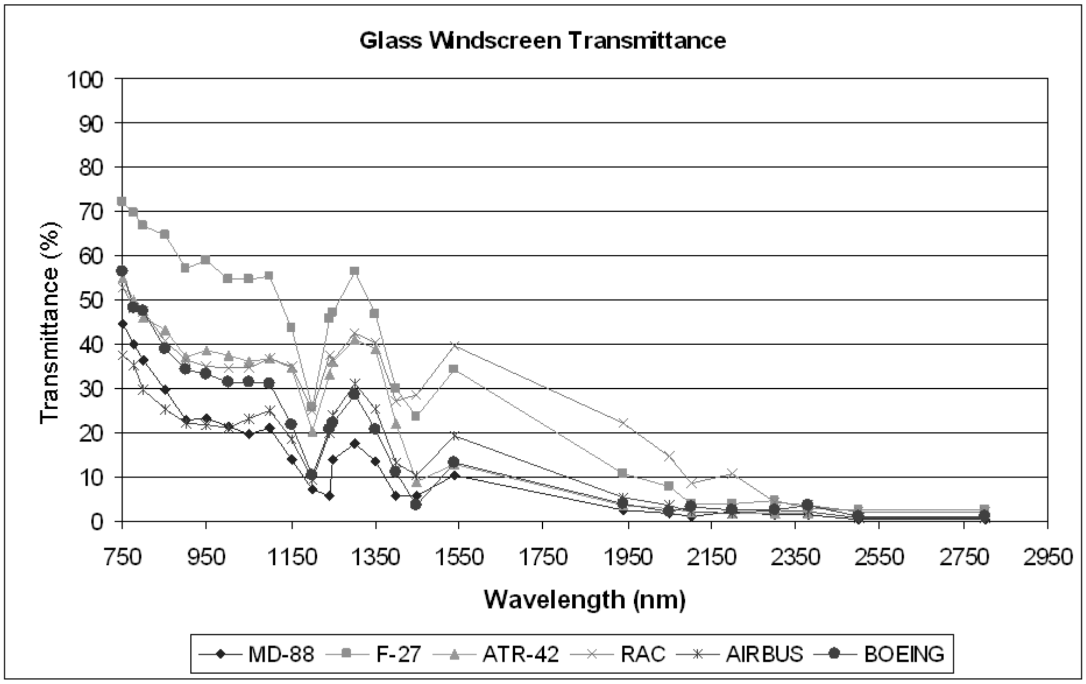

Figure 4. Transmittance of individual glass windscreens.

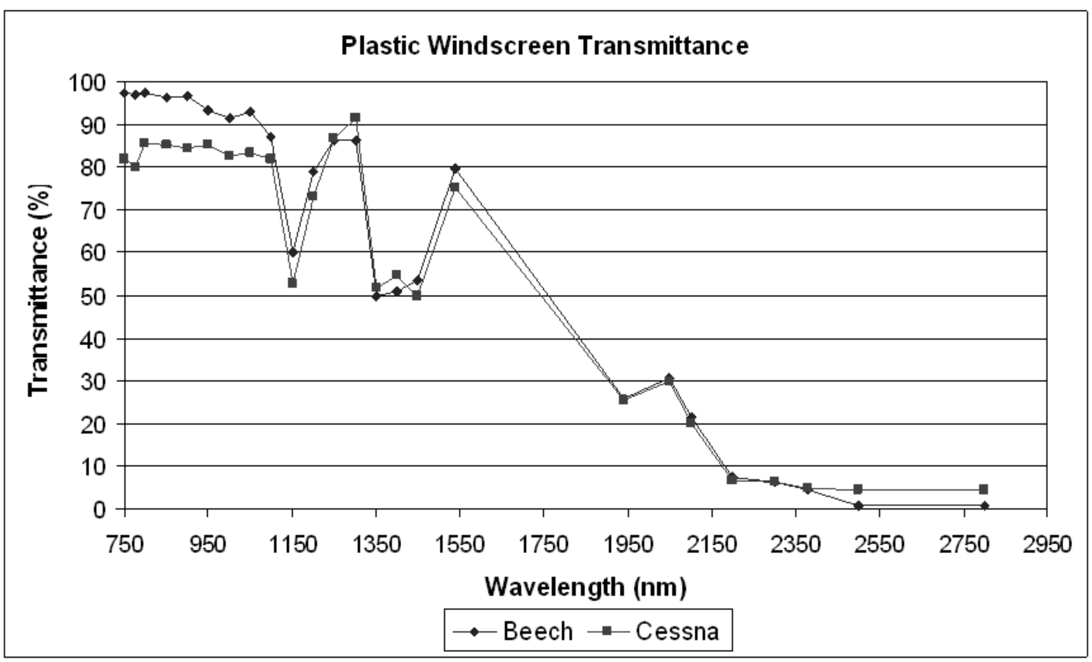

Figure 5. Transmittance of individual plastic windscreens.

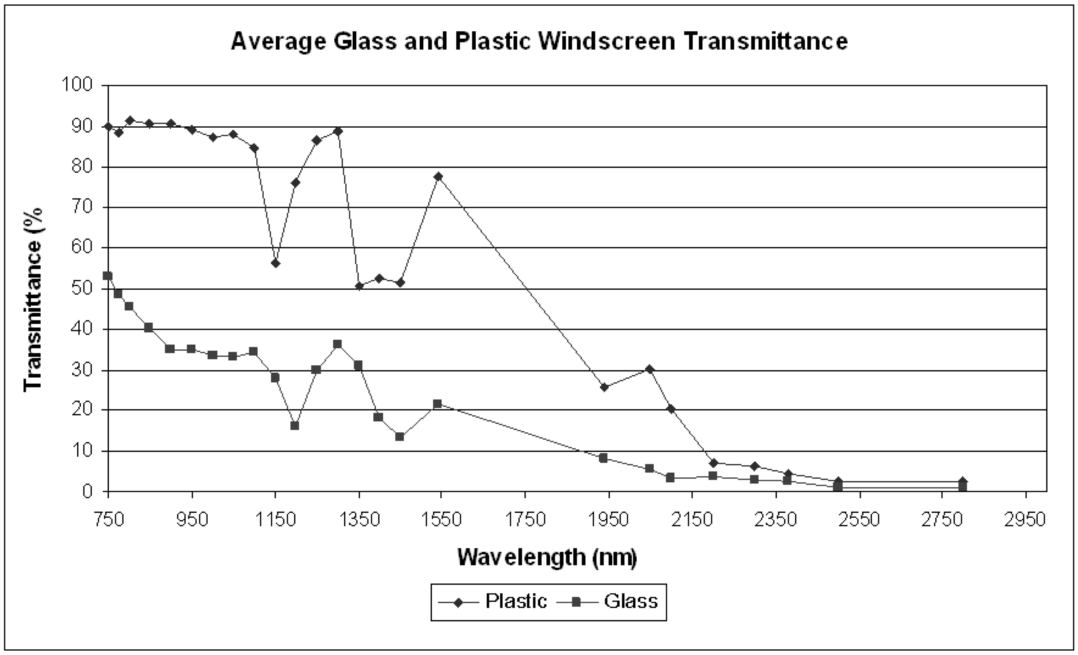

Figure 6. Average transmittance for glass and plastic windscreens.

dropped below 7%. The average transmittance for both glass and plastic windscreens gradually decreased until it became virtually immeasurable from 2800 nm through 4000 nm.

DISCUSSION

Since September 11, 2001, many analysts see the use of MANPADS as a terrorist's weapon of choice for striking U.S. airlines, especially as improvements in airport security reduce the chances for smuggling explosives or incendiary devices onto planes. There are as many as 500,000 shoulder-fired missiles in military arsenals around the world and from 5,000 to 150,000 in the hands of up to 30 non-state organizations, according to a report by the Congressional Research Service (CRS) (14). An analysis by the CRS indicates that, in the last 26 years, MANPADS have been used in attacks on 35 civilian aircraft, of which 24 were shot down, killing more than 500 people. Most of these incidents took place in war zones, principally Africa, Sri Lanka, and Afghanistan (15).

Military aircraft have been equipped with countermeasures that draw off a missile's guidance system as it attempts to lock onto the heat signature of the aircraft's engines by deploying flares from under the aircraft. After an Israeli passenger jet survived an attempt by al-Qaeda to shoot it down over Kenya in 2002, El Al Israel Airlines installed flare-based Counter-MANPAD systems on all its aircraft (16). But the fear of collateral damage from fires, should the flares be deployed by mistake, makes this solution less than optimal for most civil aviation authorities, including those in the United States.

The Counter-MANPADS program, as it is known, began in January 2004 when DHS selected three teams from a field of 24 to compete in a study to determine how infrared counter measures (IRCM) could be adapted for use on large civilian transport airplanes. The systems currently under development for U.S. carriers are housed in pods mounted on the underside of an aircraft's fuselage and employ IRCM to disrupt the guidance systems of surface-to-air missiles (Figure 7).

The IRCM system uses multiple-wavelength lasers that emit radiation in the infrared portion of the electromagnetic spectrum. Although the redundant safeguards and the relatively long exposure times that would be necessary to inflict injury reduce the risk to pilots, air traffic controllers, ground crews, and the public, IR emissions from these laser systems can be hazardous to ocular tissues and skin under certain circumstances. The type of damage an IR laser may cause depends on several factors, including the energy delivered per unit area, duration of exposure, and wavelength. Within the Nominal Ocular Hazard Distance, near-infrared (IR-A) laser radiation may damage the retina, while middle- and far-infrared laser radiations (>1,400 nm) can injure the cornea and, to a lesser extent, the crystalline lens, provided the applicable maximum permissible exposure (MPE) limit is exceeded. Damage to tissue from laser radiation is usually due to heating (thermal effects); however, photochemical injury may also occur. Most photochemical effects are limited

Figure 7. Conceptual illustration of a civilian Counter-MANPADS deploying (invisible) IRCM to disrupt the guidance systems of surface-to-air missiles.

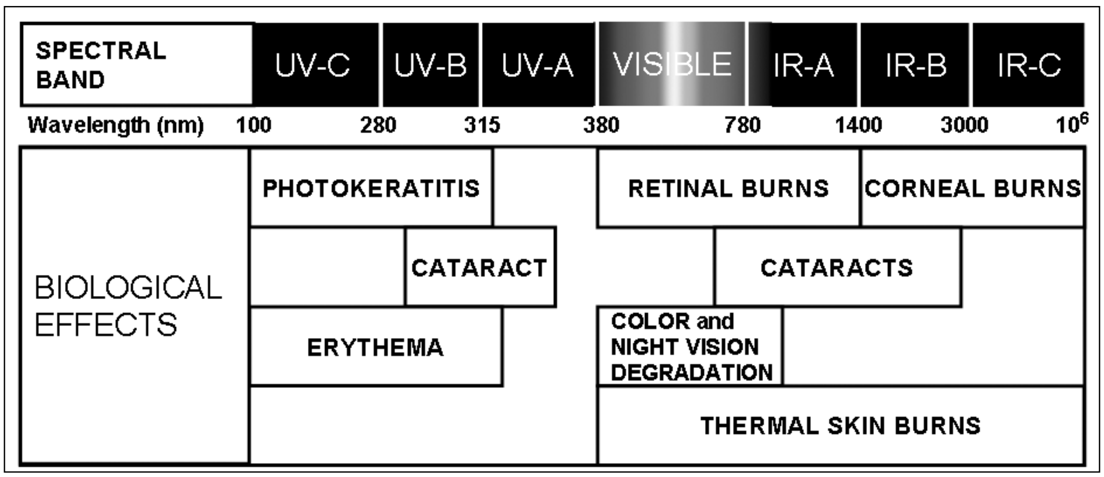

Figure 8. Potential adverse biological effects from excessive exposure to optical radiation Sliney & Wolbarsht, 1980).

to shorter wavelengths; whereas, thermal effects can occur at any wavelength in the optical radiation spectrum. A summary of the adverse biological effects that can result from excessive exposure to various wavelengths of radiation is illustrated in Figure 8. Only a very small percentage of radiation reaches the retina beyond 1,400 nm, due to absorption by tissues in the anterior portion of the eye. Mid-infrared radiation (IR-B) may penetrate anterior tissues of the eye deep into the crystalline lens, causing corneal burns and infrared cataracts. Far-infrared radiation (IR-C) is primarily absorbed by the cornea and can result in corneal burns and blurred vision. The major danger to the skin from lasers operating in the IR region of the spectrum is thermal burns. Other possible injuries include erythema and radiant heat stress. In some cases, symptoms may appear 6 – 12 hours after exposure and disappear gradually after 24 – 36 hours, leaving no permanent damage (8).

The present study found that windscreens can provide varying degrees of protection from IR radiation exposure depending on the type of windscreen material and wavelength of the radiation. Plastic material transmitted up to 40% more radiation at 780 nm. In other words, glass laminate windscreens blocked between 20 and 60% more IR radiation than plastic from 780 nm through 2,100 nm. Above 2,200 nm, both glass and plastic windscreens reduced IR transmission to 7% or less, and the difference became practically immeasurable from 2,800 nm through 4,000 nm.

The reduced transmission of windscreen materials at certain wavelengths can help to protect a pilot from ocular tissue damage. Optical density (OD), which can be calculated from transmittance (T) (i.e., $OD = Log_{10}(1/T)$), is the capacity of an optical element to absorb (attenuate) radiation of a given wavelength. The optical density for the average glass (OD_{glass}) and

plastic ($OD_{plastic}$) windscreens are presented in Figure 9. For a particular wavelength, a high transmittance value results in a low OD. Conversely, an opaque material with a transmittance near 0% would have a very high OD. The windscreens examined in this study exhibited IR transmittance between 1.3 and 91.5%, resulting in OD values that ranged from 1.9 to 0.04, respectively, with laminated glass windscreens attenuating more IR radiation than plastic windscreens. In Figure 9, two 6^{th}-order polynomial approximations were utilized to fill the gaps between the specific wavelengths and bandwidths measured using the various instruments and filters. It can be inferred that the OD values for wavelengths between 3,000 nm and 4,000 nm are at least 1.9 and 1.6 for glass and plastic, respectively.

Table 1 compares several IR lasers of different wavelengths. All lasers listed are repetitive pulsed with frequencies of 15 Hz, average power output of 300 milliwatts (mW), divergence of 1 milliradian (mrad), energy per pulse of 20 millijoules (mJ), and pulse width of 12 nanoseconds (ns). The last four columns contain the Nominal Ocular Hazard Distance (NOHD), Nominal Skin Hazard Distance (NSHD), and OD values for ocular tissues (OD_{eye}) and skin (OD_{skin}) for these lasers. These results were calculated using the LHAZ V4.0 software, developed by The Air Force Research Laboratory, Optical Radiation Branch, at Brooks AFB, TX. The NOHD and NSHD are the minimum distances that must be maintained from the laser source to avoid exceeding the MPE, respectively, for an exposure of up to 10 s. For example, a Nd:YAG (1064 nm) laser with the output parameters listed below must be at a distance of at least 2,610 m to avoid ocular tissue damage from a 10-s exposure (with atmospheric attenuation in clear air accounted for). Skin damage from this laser would be avoided beyond 5.2 m. Laser eye protection with an OD of 4.6 is required for ocular protection within the NOHD, while an OD of only 0.5 is required within the NSHD.

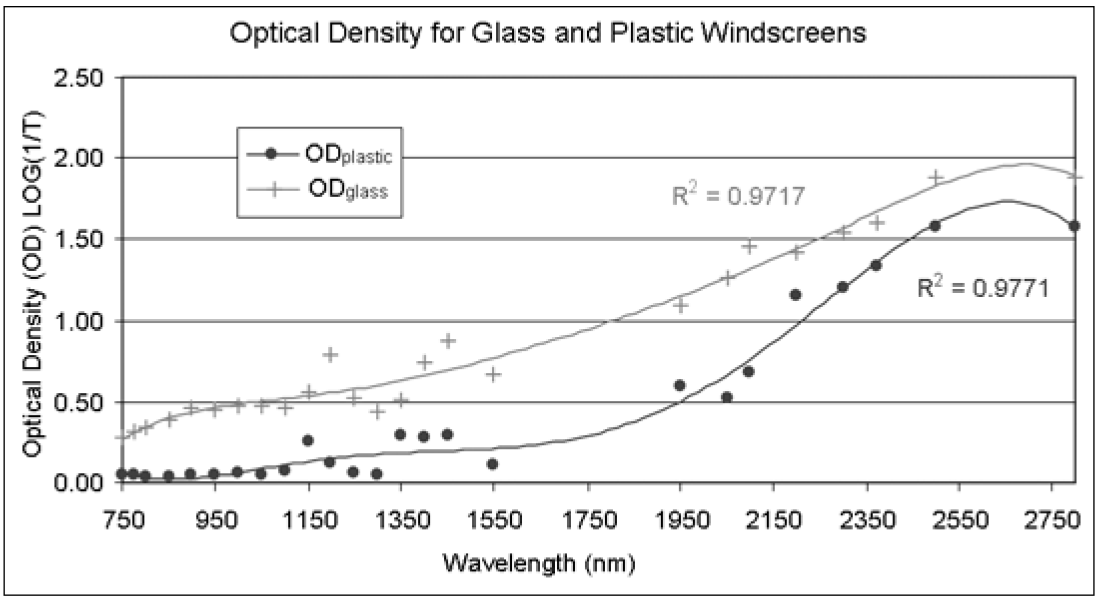

Figure 9. Mean OD values for glass laminate and polycarbonate plastic windscreens.

Table 1: Optical density values and hazard distances for selected IR lasers.

Laser Type	Wavelength (nm)	MPE ($\mu J/cm^2$)	NOHD (m)	NSHD (m)	OD_{eye}	OD_{skin}
GaAs	840	0.2722	5,730	16.6	5.28	0.91
Nd:YAG	1064	1.429	2,610	5.2	4.56	0.49
Nd:YAG	1330	11.43	938	5.2	3.66	0.49
Cr^{2+}:CdSe	2600	2,857	58.8	37.5	2.95	1.50
HeNe	3390	2,857	58.8	37.5	2.95	1.50
CO2	10600	2,857	58.8	37.5	2.95	1.50

Table 2 illustrates the reduction in both NOHDs and NSHDs for the six selected lasers when the average OD values for glass and plastic windscreens were applied to the hazard distances in Table 1. Note that attenuation of IR radiation by plastic windscreens reduced the NOHDs of the three lasers operating in the retinal hazard region (< 1,400 nm) by 4 to 28%, while glass reduced these distances by 35 to 63%. Both glass and plastic windscreens provide sufficient attenuation to eliminate any ocular and skin hazards for the example lasers operating in the IR-B and IR-C regions (> 1,400 nm) of the electromagnetic spectrum.

Aviation personnel who wear corrective spectacle lenses may add a small amount of mid-IR attenuation to that provided by windscreens. The transmittance data for clear ophthalmic lens materials are plotted in Figure 10 (17). Note that both glass and plastic lens materials transmit approximately 90% of IR radiation from 780 nm to 1,100 nm. Both crown glass and high-index (1.60) glass lenses continue to transmit high levels of IR (≥ 83%) through 2,530 nm. Plastic lenses (CR-39®, MR-6, and polycarbonate) transmit 80% to 10% of the IR radiation from 1,350 nm to 2,300 nm, respectively. Neither glass nor plastic ophthalmic lens materials provide adequate protection from IR radiation exposure in the retinal hazard region unless special treatments are added to the lens material.

Sunglass lenses designed for "general-purpose" use, made from ophthalmic glass with gray, green or tan tints, provide high IR attenuation throughout the retinal hazard

Table 2: The nominal hazard distances considering transmission losses through glass and plastic windscreens.

Laser Type	NOHD				NSHD			
	Plastic (m)	Change %	Glass (m)	Change %	Plastic (m)	Change %	Glass (m)	Change %
GaAs	5,490	4	3,740	35	15.5	7	6.1	63
Nd:YAG	2,470	5	1,520	42	3.1	40	0	100
Nd:YAG	673	28	346	63	0	100	0	100
Cr^{2+}:CdSe	0	100	0	100	0	100	0	100
HeNe	0	100	0	100	0	100	0	100
CO2	0	100	0	100	0	100	0	100

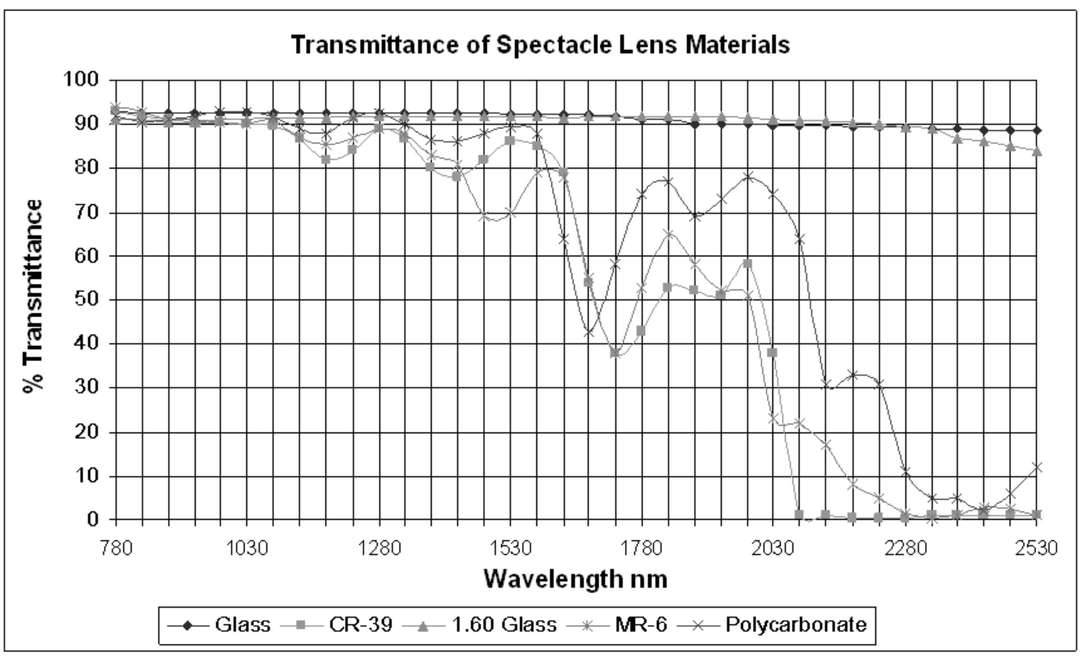

Figure 10. Transmittance of selected glass and plastic ophthalmic lens materials (adapted from: Torgersen, 1998).

region (17). These lenses also meet ANSI Z80.3 - 2001 minimum standards for transmittance of visible light and signal light recognition. Average IR transmittance, as defined by ANSI Z87.1 – 1989 (780 – 2000 nm), for the darker tints are 25.4% for tan and 6.1% for both gray and green. Some manufacturers offer infrared protection in "special-purpose" designs (i.e., sports, safety, welding, etc.) available under various trade names. Many of these lenses, however, are expensive and difficult for the general public to obtain.

In summary, the study results indicate that aircraft windscreens provide some protection from exposure to IR radiation. The amount of protection afforded by a windscreen is dependent on the type of material and the wavelength of the radiation. Generally speaking, laminated glass windscreens attenuate more IR radiation than plastic windscreens. Although normal levels of most naturally occurring atmospheric IR radiation exposure pose no serious threat, pilots may wish to take added precautions to avoid prolonged exposure to excessive levels of IR radiation. The optical densities of glass laminate windscreens can substantially reduce this risk. A laminated glass windscreen and appropriate sunglass lenses afford good protection from excessive exposure to naturally occurring visible light and IR radiation. Additional research is recommended to confirm that the measured transmittance values for this small sample of windscreens are typical of all windscreens currently in service. Finally, as applications for lasers that could be harmful to aviation personnel or passengers increase, more research may be needed to assess the potential hazards associated with their use and determine how best to mitigate their impact on aviation safety.

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